# Land Ice Modeling in CESM

William Lipscomb CESM Tutorial August 9, 2019

# Outline

- Introduction to land ice and sea level rise
- Community Ice Sheet model (CISM)
- Ice sheets in CESM2
- Coupled ice sheet climate modeling with CESM/CISM
- Antarctic ice sheet modeling
- Future directions

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### **Ice definitions**

 A glacier is a mass of ice, formed from compacted snow, flowing over land under the influence of gravity.

 An ice cap is a mass of glacier ice smaller than 50,000 km<sup>2</sup>, unconstrained by topographical features.

Glaciers and ice caps: ~43 cm sea level equivalent (SLE)



Mer de Glace, French Alps Photo by Eduard Spelterini, 1909



Iceland with Vatnajokull ice cap

# **Ice definitions**

- An ice sheet is a mass of glacier ice larger than 50,000 km<sup>2</sup> (Antarctica, Greenland).
- An ice shelf is a large sheet of floating ice attached to a grounded ice sheet.
- An ice stream is a region of fast-flowing ice in a grounded ice sheet.

Siple Coast ice streams



Photo credit: NASA



Arctic sea ice

Greenland ice sheet: 7 m SLE

Antarctic ice sheet: 60 m SLE

Ross ice shelf

~10-100 m/yr Jakobshavn Isbrae

land (with some snow cover)

> ocean (covered with sea ice and icebergs)

slower-moving Greenland Ice Sheet

Photo credit: Matthew Hoffman

# How glaciers move

- Glaciers flow downhill under the force of gravity.
- Ice deforms like a very viscous fluid. Warm ice is softer and flows faster.
- When there is water at the bed, glaciers can slide at speeds up to several km/year.
- Slowly deforming ice that is frozen at the bed is described by the shallow ice approximation.
- Ice that is sliding with little vertical shear is described by the shallow shelf approximation.



 General ice flow is described by the Stokes equations or higher-order approximations.

### How glaciers gain and lose mass



### **Greenland Ice Sheet**

- 7 m sea level equivalent
- Snowfall balanced by surface runoff and iceberg calving
- Mass loss of 280 Gt/year, 2002-2016

# Greenland ice flow speed Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

#### Greenland bed topography

Credit: Wikipedia Commons



### **Antarctic Ice Sheet**

- **60 m** sea level equivalent (**5 m** in marine-based West Antarctica)
- Accumulation balanced by flow into floating ice shelves, with little surface melting
- Mass loss of 220 Gt/year, 2012–2017



#### Antarctic ice flow speed Deglaciated Antarctic topography Credit: Global Warming Art Project



# **Global average sea level rise**

- Global mean sea level was stable for the past 3000 years, until 1900.
- Sea level has risen by about 20 cm since measurements began around 1880, with acceleration during the satellite era (since 1993).
- Current SLR: ~2/3 from land ice loss, 1/3 from ocean thermal expansion (plus regional effects such as land subsidence and glacial rebound)

#### Global average sea level change since 1880

Sea level change since 1993





GlobalChange.gov

Nerem et al. 2018

### Ice sheets in warm climates

- Last Interglacial (125,000 years ago)
  - Warming **1-2°C**, CO<sub>2</sub> = **280 ppm**
  - Global sea level 6–9 m higher than today
  - About 2 m from Greenland, 0.4 m from ocean thermal expansion, so an Antarctic contribution of at least 3 m



Pliocene (3 million years ago)

- Warming **2-3°C**, CO<sub>2</sub> = **400 ppm**
- Global sea level 5–20 m higher than today
- Up to 7 m from Greenland, 5 m from West Antarctica, and possibly some of East Antarctica



Modeled Greenland ice thickness for the Last Interglacial (Otto-Bliesner et al. 2006)

Pliocene ice sheet reconstructions (Haywood et al. 2010)

### **Projections: IPCC Fifth Assessment Report**



Likely range of sea level rise by 2100:

- **28 to 61 cm** with low greenhouse emissions (RCP2.6)
- **52 to 98 cm** with high emissions (RCP8.5)

"Only the **collapse of marine-based sectors of the Antarctic ice sheet**, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century...."

# **Community Ice Sheet Model**

**CISM2.0** was released in 2014, followed by **CISM2.1** in 2018:

- Developed on git repo at <u>https://github.com/escomp/cism</u>, described by Lipscomb et al. (GMD, 2019)
- Documentation (standalone and coupled) at <u>https://escomp.github.io/cism-docs/</u>
- Parallel dynamical core (Glissade) with a suite of higher-order velocity solvers
- Parameterizations of physical processes such as basal sliding, iceberg calving, and grounding-line migration
- Test cases with Python tools
- Coupled to CESM2



Simulated CISM2 velocities. Top: Greenland ice sheet Bottom: Ross Ice Shelf



### **CISM2** test suite

- **ISMIP-HOM**: Compare higher-order model results to community benchmarks (Pattyn et al. 2008) for problems with small-scale variations in topography and basal traction
- **Other tests**: Shallow-ice test, idealized ice shelves and ice streams, Ross ice shelf, MISMIP3d (Pattyn et al. 2013), MISMIP+ (Asay-Davis et al. 2016)



#### ISMIP-HOM Test A:

Sinusoidal pattern in basal topography at 6 grid scales (Glissade output shown by black lines)

# **Hierarchy of Stokes approximations**

- Previous generation of ice sheet models mostly used shallow-ice or shallow-shelf approximations
- Newer models (BISICLES, Elmer-Ice, ISSM, PISM, PSU, MALI, etc.) have one or more higher-order velocity solvers
- CISM2 incudes 3D higherorder, depth-integrated higher-order, SIA, and SSA



# Some CISM options

#### Velocity solver:

- Shallow-ice approximation
- Shallow-shelf approximation
- Depth-integrated HO (DIVA)
- 3D HO (Blatter-Pattyn)

#### Basal sliding:

- No sliding
- Read in basal friction parameters
- Pseudo-plastic sliding law
- Power law
- Coulomb friction law

#### Isostasy:

- No isostasy
- Elastic lithosphere, relaxing asthenosphere

#### Iceberg calving:

- Calve all floating ice
- No-advance calving front
- Calve based on ice thickness
- Calve based on eigenvalues of stress tensor ("eigencalving")

#### Sub-ice-shelf melting:

- No basal melting
- Uniform basal melt rate
- Read in basal melt rates
- Compute basal melting as a function of depth
- Compute basal melting as a function of ocean thermal forcing (from climatology or model)

### **CISM: Greenland surface ice speed**

Results from a 50,000 year Greenland spin-up on a 4 km grid:

- Surface mass balance from a regional climate model (RACMO2)
- Depth-integrated higher-order solver (DIVA; Goldberg 2011)
- Flow patterns are generally in good agreement with observations
  - Northeast Greenland Ice Stream (NEGIS) weaker than observed



*Left:* Observed speed (Joughin et al. 2010)

*Right:* Simulated speed in CISM

Red = fast, blue = slow



### **CISM: Greenland ice thickness**

Thin bias in northern and western Greenland

 Too-fast sliding and/or excessive coastal ablation

Thick bias in southwest Greenland and the northeast interior

 Too-slow sliding (NEGIS) and/or excessive coastal precipitation



Difference (m) between modeled and observed ice thickness after a 50 kyr spin-up (without ice shelves)

### **CISM: Greenland basal state**

 With pseudo-plastic sliding (Aschwanden et al. 2016) and a local till model, CISM's distribution of frozen and thawed regions agrees well with published estimates.





Synthesis of Greenland's basal thermal state from MacGregor et al. (2016) Basal water depth (m) in CISM; blue = frozen (no basal water), red = thawed (water present).

# Ice sheets in CESM1

CESM1 was released in 2010 with a preliminary ice sheet implementation (Lipscomb et al., 2013)

- Glimmer Community Ice Sheet Model (CISM1): serial code with shallow-ice dynamics
- Dynamic Greenland ice sheet with one-way coupling to land model

The **surface mass balance** (SMB) for glacier regions is computed by the land model in multiple elevation classes, then sent to the coupler and downscaled to the ice sheet grid.

- Couple ice albedo to atmosphere on hourly time scales
- Avoid duplication of snow physics
- Computational savings (land grid coarser than ice sheet grid)



# Ice sheets in CESM2

#### CISM2.1:

- Parallel, higher-order ice sheet dynamics
- Improved physics: Basal sliding, iceberg calving, grounding lines
- See Lipscomb et al. (2019) for model description and evaluation

#### Surface mass balance and coupling:

- Improved glacier surface physics in CLM (van Kampenhout et al. 2017)
- Support for two-way coupling between the Greenland ice sheet and the land and atmosphere (with dynamic landunits)



# Ice sheets in CESM2

- For most standard configurations, CISM is set to **no-evolve** 
  - Ice sheets are fixed
  - The surface mass balance (SMB) is computed in CLM for all glacier grid cells (in multiple elevation classes, if desired)
- CISM can evolve with **one-way coupling** 
  - SMB and surface temperature are passed from CLM to CISM
  - Fixed elevation and land surface types in CLM
- CISM and CLM can co-evolve with **two-way coupling** 
  - Ice sheet extent and elevation are passed from CISM to CLM
  - Dynamic landunits in CLM (glacier \Rightarrow vegetated)

Out-of-the box settings for Greenland:

4-km rectangular grid, dt = 0.2 yr, DIVA solver, pseudo-plastic slidingNo ice shelves: All floating ice calves immediately

### **CLM glacier regions and elevation classes**



### **Greenland surface mass balance in CESM2**

The surface climate of ice sheets has improved compared to CESM1:

- Deep firn model in CLM for realistic refreezing and densification
- Drag parameterization in CAM for improved surface winds
- Reduced bias in highlatitude longwave cloud forcing
- Still have a high-snowfall bias in southern Greenland, and SMB > 0 over northern tundra



Greenland surface mass balance (mm/yr). Left: RACMO regional model. Right: CESM2. Blue = accumulation, red = ablation. Courtesy of Leo van Kampenhout.

#### Antarctic snowfall in CESM2



Antarctic snowfall (mm/yr). Left: RACMO regional model simulation. *Right:* CESM2 simulation. Both plots are for 1979-2014 average climate. Courtesy of J. Lenaerts.

#### **Greenland SMB response to increased CO**<sub>2</sub>

#### Surface mass balance (mm/yr): red = accumulation, blue = ablation



#### Ice Sheet Model Intercomparison Project for CMIP6

- **ISMIP6** is the first Climate Model Intercomparison Project (CMIP) component focused on ice sheets.
  - *Primary goal*: To estimate past and future sea level contributions from the Greenland and Antarctic ice sheets, along with associated uncertainty
  - Secondary goal: To investigate feedbacks due to dynamic coupling between ice sheet and climate models, and impacts of ice sheets on the Earth system
- Includes both standalone ice sheet experiments and coupled ice sheet–climate experiments (Nowicki et al. 2016)



http://www.climate-cryosphere.org/wiki/index.php?title=ISMIP6\_wiki\_page

### CISM, CESM and ISMIP6

- 1. Analysis of CMIP6 global model results that are relevant for ice sheets (Lenaerts et al.)
- 2. Standalone ice sheet experiments based on CMIP6 model output to estimate past and future sea level rise, explore uncertainty (Lipscomb and Leguy)
- 3. Coupled climate ice sheet experiments to explore ice sheet impacts and feedbacks (Vizcaíno et al.)

#### CMIP6 experiments used by ISMIP6 (AOGCM)

- Pre-industrial control
- AMIP
- 1% per yr CO<sub>2</sub> to  $4xCO_2$
- Abrupt 4xCO<sub>2</sub>
- CMIP6 historical simulation
- ScenarioMIP SSP5-8.5 (to year 2300)
- Last Interglacial PMIP

#### Standalone ISMIP6 experiments (ISM only)

- ISM control
  - ISM for last few decades (AMIP)
- ISM for the historical period
- ISM forced by 1% per yr CO<sub>2</sub> to 4xCO<sub>2</sub>
- ISM for 21<sup>st</sup> / 23<sup>rd</sup> century (SSP5-8.5)
- ISM specific experiments to explore uncertainty

#### **Coupled AOGCM-ISM experiments**

- Pre-industrial control
- 1% per yr CO<sub>2</sub> to 4xCO<sub>2</sub>
- Historical + SSP5-8.5 (to year 2300)

## Spinning up coupled CESM2-CISM2

**Problem:** Coupled ice-sheet/climate system needs long equilibration (~10,000 ice sheet years), but is too expensive and slow for brute force. **Solution:** Iterated spin-up between fully-coupled and "all-active-but-atmosphere" simulations



- **BG compset:** all components active; synchronous ice sheet
- JG compset: all components active except data atmosphere; 10x accelerated ice sheet
- Cost of 10,000 CISM years:
  - **35 M** cpu-hr, BG with synchronous CISM
  - **3.5 M** cpu-hr, BG with 10x CISM
  - 1.7 M cpu-hr, JG/BG

### Spinning up coupled CESM2-CISM2



Greenland ice sheet thickness (m)

Results from JG/BG spinup:

- Ice sheet volume is ~8% larger than observed
- Residual mass trend of -5 Gt/yr (std. dev. 100 Gt/yr)
- Starting point for ISMIP6 coupled simulations



Courtesy of M. Löfverström and the LIWG

# Antarctic ice sheet instability

- Much of the Antarctic ice sheet is grounded below sea level (~5 m SLE in West Antarctica, 20 m in East Antarctica).
- This ice is vulnerable to intrusions of warm Circumpolar Deep Water, especially in the Amundsen Sea region.
- Unbuttressed ice on a reverse-sloping sea bed is unstable.



Schematic of marine ice sheet instability (IPCC AR5) Antarctic basal topography

#### **CISM Antarctic simulations: Spin-up**

- *Goal:* Spin up Antarctica to a steady state consistent with modern observations, given a prescribed SMB. More challenging than Greenland.
- Method: Nudge basal friction parameters (for grounded ice) and sub-shelf melt rates (for floating ice) to match the observed surface elevation.



#### **CISM Antarctic experiments: ISMIP6**

- Initialize ice sheet as desired.
- Run forward for 100 years using ocean thermal forcing from observed climatology plus CMIP model anomalies.
- CISM experiments show little change in first century, but collapse of Thwaites glacier basin (2 m s.l.e.) over several centuries.
  - Results sensitive to details of basal melting parameterization



Loss of Antarctic ice mass above flotation (s.l.e., mm) over 1000 years with anomaly thermal forcing from NorESM



Change in ice thickness (m)

# **Future CISM development**

#### Subglacial hydrology model

- Water is conserved and flows down the hydropotential gradient; basal friction evolves over time
- Improved calving law
  - Match observed calving fronts given stress and melt rates

#### Sub-shelf plume model

- Simple steady-state model of ocean circulation beneath ice shelves (based on Jenkins 2018)
- Temperature and salinity profiles from ocean model
- **Hydrofracture** (leading to calving and shelf breakup)
- **Code speedup** (e.g., better vectorization and preconditioning)
- Various software improvements (flexible time manager, reorganized config file, ...)

# Future land ice development in CESM

- Comprehensive land ice diagnostic package
- Reduce biases in **Greenland surface mass balance**
- Support a dynamic Antarctic ice sheet and paleo ice sheets in coupled simulations
- Support ice sheet ocean coupling
  - Idealized cases first, then gradually build in two-way coupling of the Antarctic ice sheet with the ocean
- Long transient simulations (several centuries to many millennia) of past and future climate

#### **Greenland surface mass balance, 1980-1999** Uniform v. variable-resolution grids



Annual GrIS  $610 \pm 116$  Gt  $557 \pm 71$  Gt +62%Blue = accumulation, red = ablation

521 ± 77 Gt 376 ± 99 Gt +39 %

Courtesy of L. van Kampenhout

### **Northern Hemisphere deglaciation**

What processes control deglaciation after the Last Glacial Maximum (21 ka)?

- Three ice sheets: Greenland, North American, Eurasian
- Send ocean temperature and salinity from POP to CISM for sub-shelf melting

*Left:* Laurentide ice flow reconstruction (Stokes et al. 2016)

*Right:* Simulated ice flow in CISM after 11 ka



#### Courtesy of M. Petrini

### CISM/MOM6 coupling

We have established a protocol for data exchange between CISM and the MOM6 ocean model



Initial simulations follow idealized community experiments (MISOMIP)



Schematic of sub-ice-shelf cavity



Sub-shelf melt rate (m/yr)

Next step: Test in a global domain with ice shelf cavities.

Courtesy of G. Marques

# Summary

- CISM2 and CESM2 include major physical, numerical, and software advances relative to CISM1/CESM1.
- The Land Ice Working Group is using these models for pathbreaking science, including standalone ice sheet and coupled ice sheet climate simulations for ISMIP6.
- Coupling of ice sheets to the land and atmosphere is fairly mature, but ice sheet–ocean coupling is still in its early stages.
- Sea level rise remains a wide-open problem, largely because of uncertainties about Antarctica.

### Land Ice Working Group info

Web page: http://www.cesm.ucar.edu/working\_groups/Land+Ice/

**Science liaison:** Gunter Leguy (gunterl@ucar.edu)

Software liaison: Kate Thayer-Calder (katec@ucar.edu)

**Co-chairs:** Jan Lenaerts (Jan.Lenaerts@colorado.edu) and Bill Lipscomb (lipscomb@ucar.edu)

#### **Upcoming meetings:**

- Winter LIWG meeting, Boulder, Jan. or Feb. 2020
- 25th annual CESM workshop, June 2020